

The Effect of Dark matter on the first stars: a new phase of stellar evolution

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Abstract. Dark matter (DM) in protostellar halos can dramatically alter the current theoretical framework for the formation of the first stars. Heat from supersymmetric DM annihilation can overwhelm any cooling mechanism, consequently impeding the star formation process and possibly leading to a new stellar phase. The first stars to form in the universe may be “dark stars”: giant ($\gtrsim 1$ AU) hydrogen-helium stars powered by DM annihilation instead of nuclear fusion. Possibilities for detecting dark stars are discussed.

PACS: 97.10.Bt, 95.35.+d, 98.80.Cq

INTRODUCTION

At a lunch with David Gross, Director of KITP and winner of the 2004 Nobel Prize, one of us (K.F.) asked him what his goals were for the Large Hadron Collider, the billion dollar accelerator at CERN in Geneva that will start taking data this spring. His answer was, “Supersymmetry, Supersymmetry, Supersymmetry.” Supersymmetry (SUSY), at this point a beautiful theoretical construct, has the capability of addressing many unanswered questions in particle theory as well as providing the underpinnings of a more fundamental theory such as string theory. If SUSY is right, then for every known particle in the universe, there is an as yet undiscovered partner. The lightest of these, known as the Lightest Supersymmetric Particle or LSP, would provide the dark matter in the universe.

The LSP is the favorite dark matter candidate of many physicists. This is true not only because of the beautiful properties of SUSY, but also because the LSP automatically has the right properties to provide 24% of the energy density of the universe. In particular, the neutralino, the SUSY partner of the W, Z, and Higgs bosons, automatically has the required weak interaction cross section and \sim GeV - TeV mass to give the correct amount of dark matter in the universe today. The SUSY particles are in thermal equilibrium in the early universe, and annihilate among themselves to produce the relic density today. It is this same annihilation process that is the basis of the work we consider here. The SUSY particles, also known as WIMPs (Weakly Interacting Massive Particles), annihilate with one another wherever their density is high enough. Such high densities are achieved in the early universe, in galactic haloes today [1, 2], in the Sun [3] and Earth [4, 5], and, as we have found, also in

the first stars [6]. As our canonical values, we will use the standard value $\langle\sigma v\rangle = 3 \times 10^{-26} \text{cm}^3/\text{sec}$ for the annihilation cross section and $m_\chi = 100$ GeV for the SUSY particle mass; but will also consider a broader range of WIMP masses (1 GeV–10 TeV) and cross-sections.

We here describe the results of our work [6] which considers the effect of SUSY dark matter annihilation on the first stars. These stars form at redshifts $z \sim 10 - 50$ in dark matter (DM) haloes of $10^6 M_\odot$ (for reviews see e.g. [7, 8, 9]). One star is thought to form inside one such DM halo. We must first ask, what is the dark matter density inside a forming protostar? To answer this question we use an adiabatically contracted NFW profile [10]. We start with an overdense region of $10^5 - 10^6 M_\odot$ with an NFW profile for both DM and gas, where the gas contribution is 15% of that of the DM. Then we use adiabatic contraction ($M(r)r = \text{constant}$) [11] and match onto the baryon density profiles given by [12, 13] to obtain DM profiles. Our resultant DM profiles are shown in Fig. 1a for concentration parameter $c = 10$ at a redshift $z = 19$ and halo mass $M = 10^6 M_\odot$. It is important to point out that our results do not change much when these parameters change; e.g. even for $c = 1$, the dark matter density only changes by a factor of 4. After contraction, the DM density at the outer edge of the baryonic core is roughly $\rho_\chi \simeq 5 \text{GeV}/\text{cm}^{-3} (n/\text{cm}^{-3})^{0.81}$ and scales as $\rho_\chi \propto r^{-1.9}$ outside the core. Our adiabatically contracted NFW profile matches the DM profile obtained numerically in [12], who also found $\rho_\chi \propto r^{-1.9}$, for both their earliest and latest profiles.

WIMP annihilation produces energy at a rate per unit volume $Q_{\text{ann}} = \langle\sigma v\rangle \rho_\chi^2 / m_\chi \simeq 1.2 \times 10^{-29} \text{erg}/\text{cm}^3/\text{s} (\langle\sigma v\rangle / (3 \times 10^{-26} \text{cm}^3/\text{s})) (n/\text{cm}^{-3})^{1.6} (m_\chi / (100 \text{GeV}))^{-1}$. In the early stages of

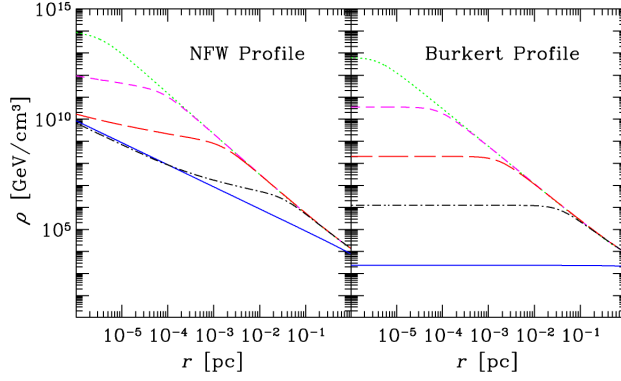


FIGURE 1. Adiabatically contracted DM profiles for (a) an initial NFW profile and (b) an initial Burkert profile [14], for $M_{\text{vir}} = 10^6 M_{\odot}$, $c_{\text{vir}} = 10$, and $z = 19$. The blue (solid) lines show the initial profile. Black (dot-dash) lines correspond to a baryonic core density of 10^7cm^{-3} , red (long-dashed) lines to 10^{10}cm^{-3} , magenta (dashed) lines to 10^{13}cm^{-3} and green (dotted) lines to $n \sim 10^{16} \text{cm}^{-3}$.

Pop III star formation, when the gas density is low, most of this energy is radiated away [15, 16]. However, as the gas collapses and its density increases, a substantial fraction f_Q of the annihilation energy is deposited into the gas, heating it up at a rate $f_Q Q_{\text{ann}}$ per unit volume. We have estimated the fraction f_Q of DM annihilation energy that remains inside the gas core. While neutrinos escape from the cloud without depositing an appreciable amount of energy, electrons and photons can transmit energy to the core.

We find that, for LSP mass $m_{\chi} = 100 \text{GeV}$ (1 GeV), a crucial transition takes place when the gas density reaches $n > 10^{13} \text{cm}^{-3}$ ($n > 10^9 \text{cm}^{-3}$). Above this density, most of the annihilation energy remains inside the core and heats it up to the point where further collapse of the core becomes difficult. To compare with DM heating, we include all relevant cooling mechanisms. The dominant mechanism is H_2 cooling; we use the rates in [17]. We use the opacities from [18]; e.g. at $n \sim 10^{13} \text{cm}^{-3}$, we take a $\sim 8\%$ cooling efficiency. Setting the heating rate equal to the cooling rate gives the critical temperature $T_c(n)$ at a given density n below which heating dominates.

In figure 2 we compare $T_c(n)$ to typical evolution tracks in the temperature-density phase plane. The blue (solid) and green (dotted) lines show the temperature evolution of the protostellar gas in the simulations (without DM) of [18] and [13] respectively. The red (dashed and dot-dashed) lines show the critical temperature: below these lines, DM heating dominates over all cooling mechanisms.

Figure 2 illustrates results for a range of WIMP masses from 1 GeV–10 TeV for a canonical $3 \times 10^{-26} \text{cm}^3/\text{sec}$ annihilation cross-section. Since the heating rate scales

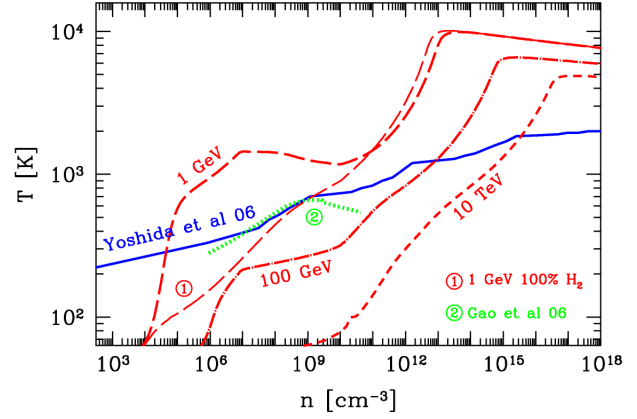


FIGURE 2. Comparison of critical temperature (red dashed lines) to typical evolution tracks in the temperature-density phase plane. The blue (solid) and green (dotted) lines show the protostellar gas evolution from simulations of [18] and [13] respectively. The red dashed lines mark $T_c(n)$ for: (i) $m_{\chi} = 1 \text{ GeV}$ with H_2 density from simulations, (ii) $m_{\chi} = 1 \text{ GeV}$ assuming 100% H_2 , (iii) $m_{\chi} = 100 \text{ GeV}$ and (iv) $m_{\chi} = 10 \text{ TeV}$. At the crossing point of the blue/green and red lines, DM heating dominates over cooling in the core's evolution.

as $\langle \sigma v \rangle / m_{\chi}$, these same curves equivalently apply to a variety of cross-sections for a given WIMP mass.

The important result is that the blue/green (evolutionary) and red (critical temperature) lines always cross, regardless of WIMP mass or H_2 fraction: this is a robust result. As soon as the core density reaches this crossing point, the DM heating dominates inside the core and changes its evolution. Notice that at $m_{\chi} = 1 \text{ GeV}$, the crossing point for small H_2 fraction is at low densities, around $n \sim 10^5 \text{cm}^{-3}$, in agreement with [15]. If the H_2 fraction is increased, cooling dominates for a longer time, as expected, but not forever. Our results were obtained for two possible values for the H_2 fraction: the value given by the simulations without DM, and the case of 100% molecular hydrogen.

As soon as the DM annihilation products are contained inside the protostellar core, the heating dominates over the cooling. Hence, for 100 GeV (1 GeV) neutralino DM, once the gas density reaches a critical value of $\sim 10^{13} \text{cm}^{-3}$ (10^9cm^{-3}), the heating rate from DM annihilation exceeds the rate of hydrogen cooling. The protostellar core is *prevented from cooling and collapsing* further. The size of the core in the standard Pop III models at this point is $\sim 17 \text{ A.U.}$ ($\sim 960 \text{ A.U.}$) and its mass is $\sim 0.6 M_{\odot}$ ($\sim 11 M_{\odot}$); we plan to compute the stellar structures of the “dark stars” to see what alternative size and mass result. Our main conclusion is that the standard picture of Pop III star formation is drastically modified by neutralino dark matter annihilation inside the protostellar object.

We propose that a new type of object is created, a “dark star” supported by DM annihilation rather than fusion. The question is how long such a phase of stellar evolution lasts. If such an object were stable for a long time period, it would even be possible for these dark stars to still exist today. Dark stars could last as long as the DM annihilation timescale, $\tau_e = m_\chi / (\rho_\chi \langle \sigma v \rangle) \simeq 0.6 \text{ Gyr } (n/10^{13} \text{ cm}^{-3})^{-0.8} (m_\chi/100 \text{ GeV}) (\sigma v/3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1})^{-1}$. For our canonical case, we find $\tau_e \sim 600 \text{ Myr } (\sim 15 \text{ Myr})$ for $n = 10^{13} \text{ cm}^{-3}$ ($n = 10^{15} \text{ cm}^{-3}$). By comparison, the entire timescale for collapse (without taking into account DM annihilation) is $\sim 1 \text{ Myr}$ at $z = 50$ or 100 Myr at $z = 15$; even for the more recent episodes, the dynamical time at the high densities considered here is very short ($< 10^3 \text{ yr}$). However, after this DM annihilates away, it is possible that the DM hole in the small central core can fill in again, depending on the DM orbits at this stage. DM further out can also continue to heat the core. On the other hand, as baryons continue to accrete onto the protostar, it is possible that the annihilation shuts down sooner. The lifetime of the dark star phase is crucial to addressing the question of the effects it has on the universe.

The effects of such a new phase of stellar evolution could be very interesting. The reionization of the IGM could be quite different, as would be the production of the heavy elements required to form all future generations of stars. DM heating may also alter the mass of Pop III stars. Due to DM heating the initial mass function for Pop III stars could be modified. On the one hand the DM heating could prevent further accretion of baryons [19] so that the resulting stars are less massive. Alternatively the initial protostellar object may be larger and dark stars might accrete enough material [20] to form large black holes [21, 22] en route to building the $10^9 M_\odot$ black holes observed at $z \sim 6$.

What are the observational consequences of a “dark star”? Dark stars are giant objects, with core radii $\gtrsim 1 \text{ AU}$; perhaps they could be found by lensing experiments. The DM annihilation products may be seen in detectors on Earth today, e.g. neutrinos travel great distances without interacting and might be seen in e.g. AMANDA or ICECUBE. It is interesting to imagine that DM could be discovered in this way. Or, if it is previously discovered elsewhere, then its properties (mass and cross-section) could be studied. The photons resulting from the annihilation could contribute to the γ -ray background and could be seen by GLAST or atmospheric Cherenkov telescopes such as HESS, VERITAS, and MAGIC. Alternatively, if the DM heating slows down but does not entirely hinder the Pop III collapse, the difference of the expected evolution from the more standard scenario could be seen in the next generation of telescopes such as JWST.

ACKNOWLEDGMENTS

This project would not have come into existence without the help of Pierre Salati. We are also particularly grateful to Chris McKee for many useful conversations as well as his encouragement. We also thank A. Aguirre, P. Madau, F. Palla, J. Primack, R. Schneider, S. Stahler, G. Starkman, and N. Yoshida for discussions. K.F. acknowledges support from the DOE and MCTP via the Univ. of Michigan; from the Miller Inst. at UC Berkeley; and thanks the Physics Dept. at UCSC. D.S. and K.F. thank the Galileo Galilei Inst. in Florence, Italy, for support. P.G. acknowledges NSF grant PHY-0456825. D.S. acknowledges NSF grant AST-0507117 and GAANN.

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